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RESEARCH MEMORANDUM

IGNITION-ENERGY REQUIREMENTS IN A SINGLE TUBULAR COMBUSTOR

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

IGNITION-ENERGY REQUIREMENTS IN A SINGLE TUBULAR COMBUSTOR

By Hampton H. Foster

SUMMARY

An investigation was conducted to determine the minimum spark energy required for ignition in a single tubular combustor. Data were obtained at simulated static sea-level engine starting conditions for a wide range of ambient temperatures, and also for a range of altitude inlet-air pressures and air-flow rates. The inlet-air pressure and flow rates limiting ignition are compared with those limiting steady-state burning in the combustor. Three different fuels were used to indicate the effect of fuel volatility on ignition.

A decrease in ambient temperature from 70° to -60° F at sea-level engine-cranking conditions required an increase in spark energy from 0.022 to about 1.5 joules for ignition in the combustor with the least volatile fuel investigated; comparable trends were obtained with more volatile fuels. The altitude ignition limits were extended by increasing the spark energy above that of the conventional system. A spark energy of approximately 10 joules per spark at a sparking rate of 8 per second gave satisfactory ignition at combustor-inlet conditions close to the steady-state burning limits of the combustor at low and intermediate air-flow rates. The ignition-energy requirements at both sea-level and altitude combustor-inlet conditions generally decreased with an increase in fuel volatility.

INTRODUCTION

Reliable ignition in the turbojet engine is important at sea-level conditions prior to take-off of the aircraft. It is particularly vital at altitude for restarting of an engine in which combustion blow-out has occurred and for the starting of auxiliary thrust engines. The altitude starting problem has become more critical as the steady-state operational limits of the engine have increased.

Fundamental experiments (reference 1) have shown that decreases in pressure require very large increases in ignition energy; for example, with a mixture of propane and air under ideal conditions for ignition

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(optimum composition, homogenous, quiescent mixture) the ignition energy must be increased from 0.27 to 34 millijoules, or about 125 times, for a reduction in pressure from atmospheric (sea level) to 1/10 atmospheric pressure (pressure at 55,000-foot altitude). Large increases in ignition energy are also required for departures in the fuel-air ratio to either the lean or rich side of an optimum value near stoichiometric.

The conditions in the actual combustor can be far from the ideal conditions for ignition represented in reference 1. The turbojet-engine fuel is a liquid that must be sprayed into the combustor in a prescribed pattern, atomized, vaporized, and so mixed with the air in the zone of the spark plug that a favorable fuel-air ratio is obtained, despite the very short time available as the fuel-air mixture flows past the spark-plug electrodes.

Research is being conducted at the NACA Lewis laboratory on full-scale engines and on single combustors to determine the relative importance of the several factors affecting ignition with a view to extending the altitude starting limits of the engine (references 2 to 4). References 2 and 3 report results of the effect of fuel volatility on the altitude starting limits of a full-scale turbojet engine and a single tubular combustor, respectively. Reference 4 presents results of an investigation conducted on a full-scale axial-flow turbojet engine in the NACA Lewis altitude wind tunnel to determine the operational characteristics of several ignition systems (with conventional spark energies and different spark-plug locations in the combustor) for a range of simulated flight conditions.

The investigation reported herein was conducted to determine the energy requirements for ignition in a single tubular combustor. The following data were obtained with three turbojet engine fuels of different volatility:

1. The ignition energy requirements for combustor-inlet conditions simulating sea-level engine cranking for an ambient temperature range of 70° to -60° F.

2. The ignition energy requirements for a range of combustor inlet-air pressures and flow rates at constant inlet-air and fuel temperatures.

3. Comparisons of the combustor inlet-air pressures and flow rates limiting ignition with those limiting steady-state burning.

FUELS

The following three fuels of current interest for use in turbojet engines were chosen for the ignition studies:

1. JP-1 (MIL-F-5616, NACA fuel 48-306), a low-volatility fuel with a Reid vapor pressure of 0 - 0.2 pound per square inch.

2. JP-3 (MIL-F-5624, NACA fuel 50-174) a high-volatility fuel, with a Reid vapor pressure of 6.5 pounds per square inch.

3. Modified JP-3 fuel (NACA fuel 49-246) obtained by removing volatile components from a MIL-F-5624 stock to adjust the Reid vapor pressure to a nominal 1.0 pound per square inch. (In this report, this modified fuel will be referred to as the 1-pound fuel.)

Analyses of the three fuels are given in table I. Distillation curves of the three fuels are presented in figure 1.

APPARATUS

Combustor

A diagram of the single-combustor installation is shown in figure 2. Air flow to the combustor was measured by a square-edged orifice plate installed according to ASME specifications and located upstream of all regulating valves. The inlet-air temperature was regulated by the use of electric heaters and refrigerated air. The combustor-inlet air quantities and pressures were regulated by remote-control valves in the laboratory air-supply and exhaust systems. Instrumentation for indicating total pressures and temperatures at the inlet and exhaust of the combustor is described in reference 5.

A section through the upstream end of the combustor showing the relative position of the spark plug and fuel-spray nozzle is shown in figure 3. A variable-area fuel-spray nozzle (reference 6) was used because a satisfactory spray could be obtained at considerably lower fuel-air ratios than with the standard simplex nozzle. The included angle of the conical spray, as observed in still air, varied from 100° to 90° for the fuel-flow range investigated. The fuel system, described in reference 3, included a refrigeration system with suitable controls for regulating temperature of the fuel to the burner. Fuel flow rates to the combustor were measured by rotameters calibrated for each fuel.

Ignition System

The ignition system consisted of a special high-energy power supply and controls so that the voltage, condenser capacitance, and sparking rate could be varied through wide limits, allowing a variation in spark energy from several millijoules to about 16 joules. Figure 4 shows a block diagram of the essential circuit configuration. A standard aircraft-type spark plug was used. Because the high spark energy eroded the electrode points very rapidly, the sparking time for each ignition start was limited to 30 to 45 seconds and the sparking rate was maintained at 7 to 8 sparks per second except where otherwise noted. Preliminary tests indicated that ignition limits were unaffected by increasing the sparking rate from 8 to 45 per second at one moderate (0.72 joule) constant spark energy. 2091

The energy was calculated as (reference 7)

$$E = \frac{1}{2} C V^2 \tag{1}$$

where

E energy, joules

C capacitance, farads

V voltage, volts

PROCEDURE

The sea-level ignition tests were conducted at conditions simulating a sea-level engine cranking speed of about 9-percent normal rated rpm for a simulated ambient temperature range from 70° to -60° F. The corresponding combustor inlet-air pressures, temperatures, and flow rates (lb/sec/sq ft based on a combustor maximum cross-sectional area of 0.267 sq ft) are shown in figure 5. Fuel at the simulated temperature was admitted to the burner by opening the throttle slowly until ignition was obtained, allowing a maximum time interval of about 30 seconds for ignition. The occurrence of ignition was indicated by a temperature rise in the combustor. The criterion for satisfactory ignition was that the flame fill the combustor and continue burning after the spark was de-energized.

Prior to the altitude ignition investigation, the steady-state burning limits of the combustor were determined as a basis for judging the ignition requirements of the combustor. At conditions (-10° F inlet-air temperature and -40° F fuel-inlet temperature) representative of inlet temperatures for altitude engine-windmilling, the minimum and maximum fuel-flow rates at which steady-state burning could be obtained were determined for a range of inlet-air pressures and flow rates.

The procedure in obtaining the altitude ignition data was to choose a pressure, higher than the burning-limit pressure, at each air-flow rate and by trial to determine the minimum spark energy required for satisfactory ignition. This procedure was repeated for successively lower pressures until a limiting pressure was reached where ignition was not possible, even with an energy of 10 joules per spark. The inlet-air and fuel temperatures were maintained at the same values as in the determination of the steady-state burning limits.

It was desired to obtain ignition limits with a system typical of current practice in order to compare these limits with those obtained with the nonconventional high-energy systems investigated. Several conventional turbojet ignition systems provide from 0.016 to 0.033 joule at sparking rates from 400 to 800 per second. A number of tests were therefore made with the ignition energy set at 0.025 joule and the sparking rate at 200 per second (the maximum rate permissible with the test apparatus); this system is referred to as the "conventional" ignition system.

RESULTS AND DISCUSSION

Ignition at Sea-Level Conditions

The effect of ambient temperature on the minimum spark energy required for successful combustor ignition at simulated sea-level engine cranking conditions is shown in figure 6. The spark energies required increased rapidly with a decrease in ambient temperature for the three test fuels. For example, the 1-pound fuel required 0.007 joule for ignition at 27° F, but required 1.0 joule at -60° F, or an increase of 143 to 1. The most volatile fuel, JP-3, required the least ignition energy at the lower ambient temperatures, which is in agreement with the trends presented in reference 3 with constant spark energy. The low volatility fuel, JP-1, required the highest ignition energy and the results were the least consistent, as indicated by the scatter of the data for this fuel. With JP-1 fuel, the required energy increased from 0.022 to 1.5 joules as the ambient temperature was decreased from 70° to -60° F.

The results shown are for a sparking rate of 8 per second. At very high sparking rates such as are used in conventional ignition systems the spark energies required would probably be somewhat lower, particularly in the low energy range. The differences in spark energy required for the 3 fuels might also be affected by large changes in sparking rate.

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Altitude Steady-State Burning Limits

The results of the steady-state burning-limit investigation are shown in figure 7 for the three fuels. At any fuel-air ratio, stable combustion may be obtained only at a pressure above the limiting pressure indicated by the curve. The general shapes of the burning limit curves are similar. The minimum pressure at which combustion may be maintained decreases with a decrease in air-flow rate. The fuel-air ratio required for burning at minimum pressures was relatively unaffected by air flow except at very low air-flow rates. The displacement of the lowest air-flow curve (0.37 lb/(sec)(sq ft)) to higher fuel-air ratios can be attributed to poor fuel-spray characteristics at the attendant low fuel-flow rates. By replacing the variable-area fuel nozzle with a smaller nozzle (nominal 4.5 gal/hr at 100 lb/sq in. nozzle pressure) that would produce a satisfactory spray at lower fuel flow rates, the curve for 0.37 pound per second per square foot was shifted to lower fuel-air ratios with little significant change in the minimum pressure limit (fig. 7(c)). The minimum pressures and the corresponding air-flow rates from figure 7 are plotted in figure 8 to compare the burning limits at optimum fuel-air ratio for the three fuels. These curves represent the limits of steady-state burning and, hence, the limiting air-flow rates and pressures at which ignition is possible. Slightly lower pressure limits were obtained with the more volatile JP-3 fuel; however, this difference in limiting pressure was only about 1.5 inches of mercury.

Altitude Ignition

The minimum ignition-energy requirements, at optimum fuel-air ratios, for the three fuels are shown in figure 9. With the volatile JP-3 fuel (fig. 9(a)), a large increase in spark-energy requirements accompanies a decrease in combustor pressure until a limiting pressure is approached below which ignition could not be obtained even with very high spark energies. Also at constant combustor-inlet pressure, an increase in air-flow rates (or air velocity) requires an increase in spark energy. The same trends may be observed for the less volatile 1-pound fuel (fig. 9(b)) except that the curves would probably become parallel to the energy-scale ordinate at higher spark energies. Data for the low-volatility JP-1 fuel are shown in figure 9(c). Exceptions to the regular trend of ignition energy with air flow, which was observed with the more volatile fuels, are evident in figure 9(c). As in the case of the sea-level ignition investigation, ignition with this low-volatility fuel was erratic and unpredictable.

A cross plot of the ignition data of figure 9 is shown in figure 10. Combustor inlet-air pressure is plotted against air-flow rate for constant spark energies; the burning-limit curves (fig. 8) are included for comparison. Any point on an energy line represents the minimum spark energy required for ignition at the particular pressure and air-flow condition. With the JP-3 and 1-pound fuels (figs. 10(a) and (b)), an increase in spark energy from 0.025 joule to 10 joules extended the limits of ignition to conditions approaching the burning limits of the combustor, particularly at intermediate and low air-flow rates. It would appear that only very small gains could be expected for spark energies greater than 10 joules for these more volatile fuels.

The dotted curve in figure 10 shows ignition limits obtained with the "conventional" system, 0.025 joule per spark and 200 sparks per second. The improvement shown in figure 10(a) of the conventional 0.025-joule curve over the 0.025-joule curve obtained from the data of figure 8 is due to the higher sparking rate (200 per second); however, in preliminary tests with a higher spark energy (0.72 joule), increasing the sparking rate from 8 to 45 per second had little effect on ignition limits. It may be surmised that ignition of sprayed cold fuel is aided when spark electrodes become hot enough to produce appreciable vaporization of the fuel droplets striking them. For the low-energy (0.025 joule) case, the increase in sparking rate may have appreciably increased the temperature of the spark electrodes, whereas for the higher energy (0.72 joule) case, the electrode temperature may have been sufficiently high over the range of sparking rates investigated.

With the conventional energy of 0.025 joule, ignition could not be obtained at as low pressures (or high air-flow rates) with the 1-pound fuel as with the JP-3 fuel; however, the response to increases in energy was greater with the 1-pound fuel. This observation is possibly indicative of the necessity for high spark energies to vaporize fuel since a spark of 1 joule or more supplies a large excess of energy over that required for ignition of ideal mixtures at the pressure encountered (reference 1).

Data for the lowest volatility fuel, JP-1, are presented in figure 10(c). Increasing the spark energy from the conventional 0.025 joule to 10 joules allowed increases in the ignition limits comparable to those obtained with the 1-pound fuel at high and intermediate air-flow rates. At low air-flow rates with the lowest volatility fuel, the constant-energy curves show an increase in limiting pressure with a decrease in air-flow rate; this is contrary to the trends observed with the more volatile fuels and is probably due to insufficient vaporized fuel in the vicinity of the spark when the lowest volatility fuel is sprayed into a low-velocity air stream.

A comparison of the ignition limits of the three fuels is shown in figure 11 for a spark energy of 10 joules. The more volatile fuel (JP-3) has slightly lower pressure ignition limits than the 1-pound fuel. At intermediate air-flow rates, the ignition limits of the least volatile fuel (JP-1) were similar to those of the more volatile fuels; at low and high air-flow rates, however, they were inferior to those of the more volatile fuels. 2091

The differences in the boundaries of ignition and the burning limit curves indicated in figure 10 are smallest at the intermediate air-flow rates for the lowest volatility fuel and at the intermediate and low air-flow rates for the higher volatility fuels. The lower air-flow rates represent the range of conditions that would probably be encountered in attempted engine starts at altitude windmilling conditions. The actual operational limits of the turbojet engine would occur at somewhat higher pressures than the burning limits that have been presented, because the combustor must not only sustain combustion but must also produce sufficient temperature rise to operate the engine. A spark energy of 10 joules, therefore, appears to be sufficient for ignition in the combustor at most engine operating conditions. Also, as shown in figure 11, a spark energy of 10 joules will provide equally satisfactory ignition of both low and high volatility fuels over a wide range of operating conditions.

Reproducibility

The tailed points shown in figures 9(a) and 9(b) represent check data obtained not only to extend the ignition-limit curves but also to indicate, to a limited extent, the reproducibility of the results. In general, the reproducibility improved with an increase in fuel volatility and with an increase in spark energy. Similarly, ignition with the more volatile fuels was obtained more consistently, and in a shorter time interval than with the lower volatility fuels.

SUMMARY OF RESULTS

The following results were obtained from an investigation of the spark-energy requirements for ignition in a single tubular turbojet-engine combustor operated with three fuels of different volatility.

1. For ignition at simulated sea-level engine cranking conditions, a decrease in ambient temperature from 70° to -60° F required an increase in spark energy from 0.022 to about 1.5 joules for the lowest volatility fuel investigated; comparable trends were obtained with more volatile fuels.

2. The altitude ignition limits were extended by increasing the spark energy above that of the conventional ignition system. A spark energy of approximately 10 joules per spark at a sparking rate of 8 per second gave satisfactory ignition at combustor-inlet conditions approaching the steady-state burning limits of the combustor at low and intermediate air-flow rates.

3. For most of the conditions investigated the higher volatility fuel required less ignition energy than the lower volatility fuels.

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National Advisory Committee for Aeronautics,
Cleveland, Ohio.

REFERENCES

1. Scull, Wilfred E.: Relationship Between Inflammables and Ignition Sources in Aircraft Environments. NACA TN 2227, 1950.

2. Wilsted, H. D., and Armstrong, J. C.: Effect of Fuel Volatility on Altitude Starting Limits of a Turbojet Engine. NACA RM E50G10, 1950.

3. Rayle, Warren D., and Douglass, Howard W.: Investigation of Ignition Characteristics of an AN-F-32 and two AN-F-58a Fuels in Single Can-Type Turbojet Combustor. NACA RM E50H16a, 1950.

4. Golladay, Richard L., and Bloomer, Harry E.: Investigation of Altitude Starting and Acceleration Characteristics of J47 Turbojet Engine. NACA RM E50G07, 1950.

5. Dittrich, Ralph T., and Jackson, Joseph L.: Altitude Performance of AN-F-58 Fuels in J33-A-21 Single Combustor. NACA RM E8L24, 1949.

6. Gold, Harold, and Straight, David M.: Gas-Turbine-Engine Operation with Variable-Area Fuel Nozzles. NACA RM E8D14, 1948.

7. Swett, Clyde C., Jr.: Spark Ignition of Flowing Gases. I - Energies to Ignite Propane - Air Mixtures in Pressure Range of 2 to 4 Inches Mercury Absolute. NACA RM E9E17, 1949.

8. Gooding, Richard M., and Hopkins, Ralph L.: The Determination of Aromatics in Petroleum Distillates. Papers Presented before Div. Petroleum Chem., Am. Chem. Soc. (Chicago, Ill.), Sept. 9-13, 1946, pp. 131-141.

TABLE I - FUEL ANALYSIS

	JP-1 MIL-F-5616 (NACA fuel 48-306)	JP-3 MIL-F-5624 (NACA fuel 50-174)	Modified JP-3 (NACA fuel 49-246)
ASTM distillation, °F			
Initial boiling point	340	114	210
Percent evaporated			
5	350	128	224
10	355	138	243
20	360	149	276
30	364	160	302
40	367	174	328
50	375	188	355
60	380	204	384
70	384	231	413
80	391	330	441
90	402	439	478
Final boiling point	440	533	560
Residue, percent	1.0	1.0	1.0
Loss, percent	1.0	1.0	1.0
Freezing point, °F	<-76	-72	<-76
Aromatics, percent by volume			
Silica Gel[a]	15	5.7	23.5
Viscosity, centistokes at			
-40° F	9.2	1.65	4.28
Bromine number	0	0.9	7
Reid vapor pressure, lb/sq in.	0-0.2	6.5	1.0
Hydrogen-carbon ratio	0.154	0.172	0.157
Heat of combustion, Btu/lb	18,530	18,800	18,560
Specific gravity	0.830	0.725	0.803
Accelerated gum, mg/100 ml	0	------	------
Air jet residue, mg/100 ml	1	------	------
Sulfur, percent by weight	<0.02	------	------

[a]Determined by modified method of reference 8.

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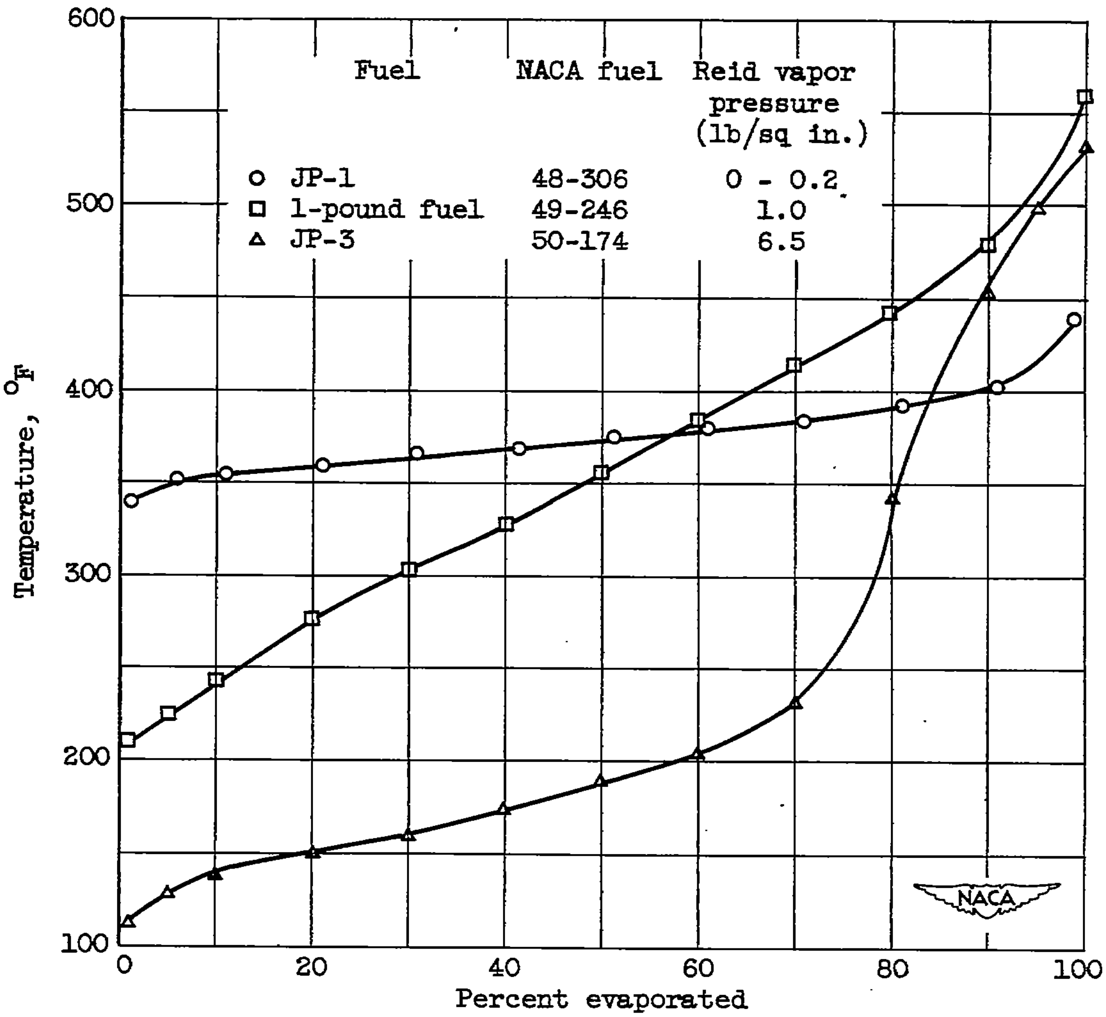

Figure 1. - Variation of distillation temperature with percentage evaporated for three fuels.

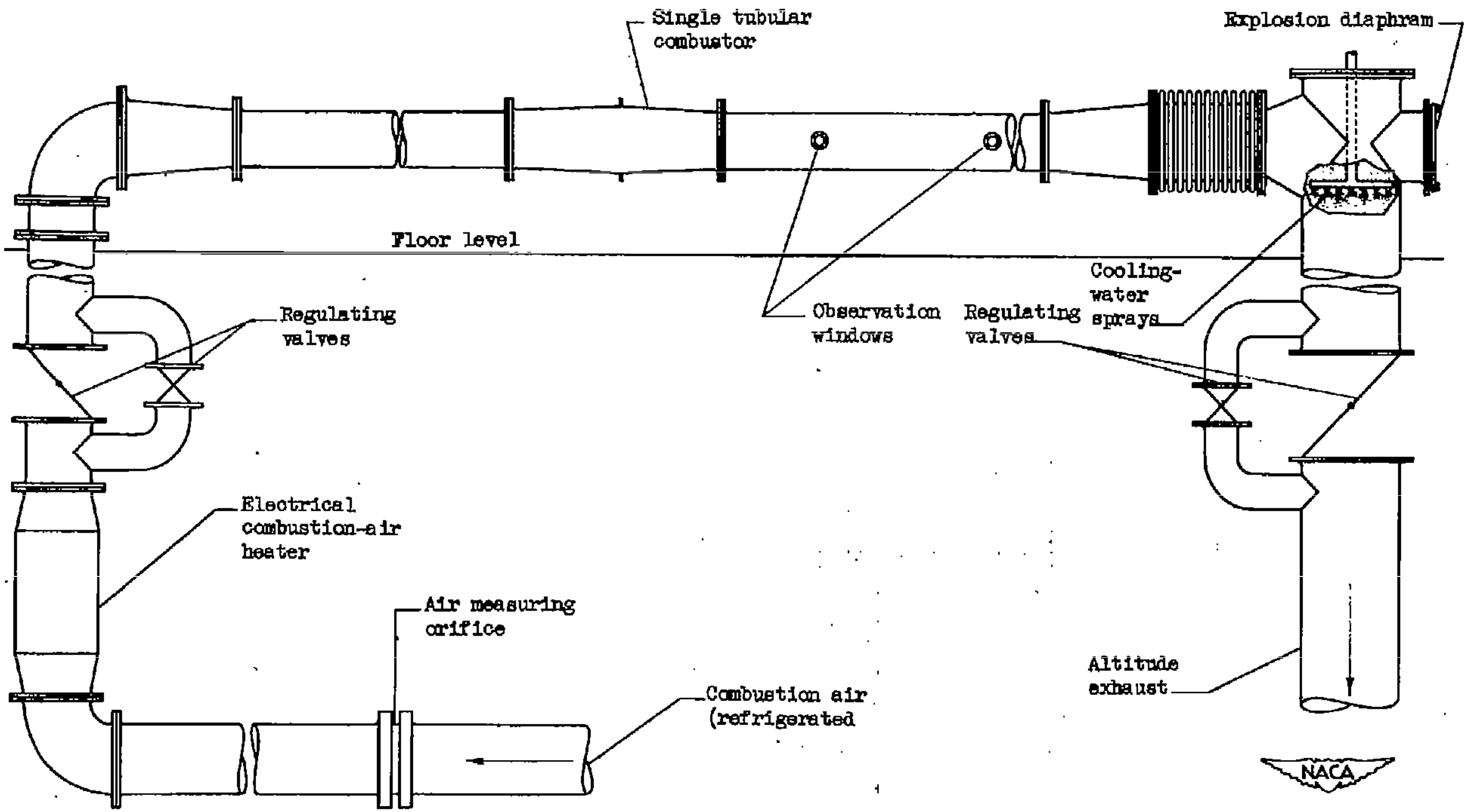

Figure 2. - Single tubular combustor installation showing inlet and outlet ducting.

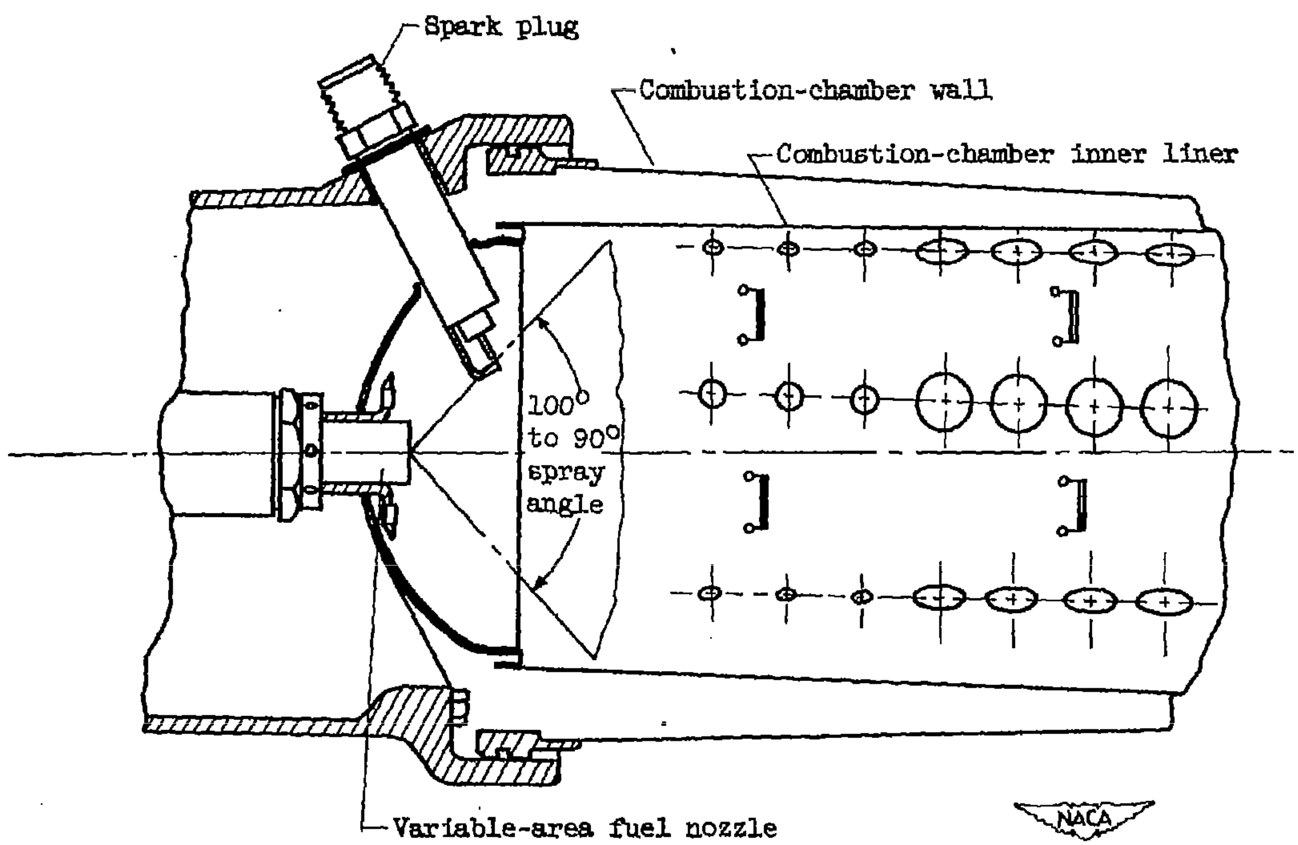

Figure 3. - Diagrammatic cross section of single tubular combustor.

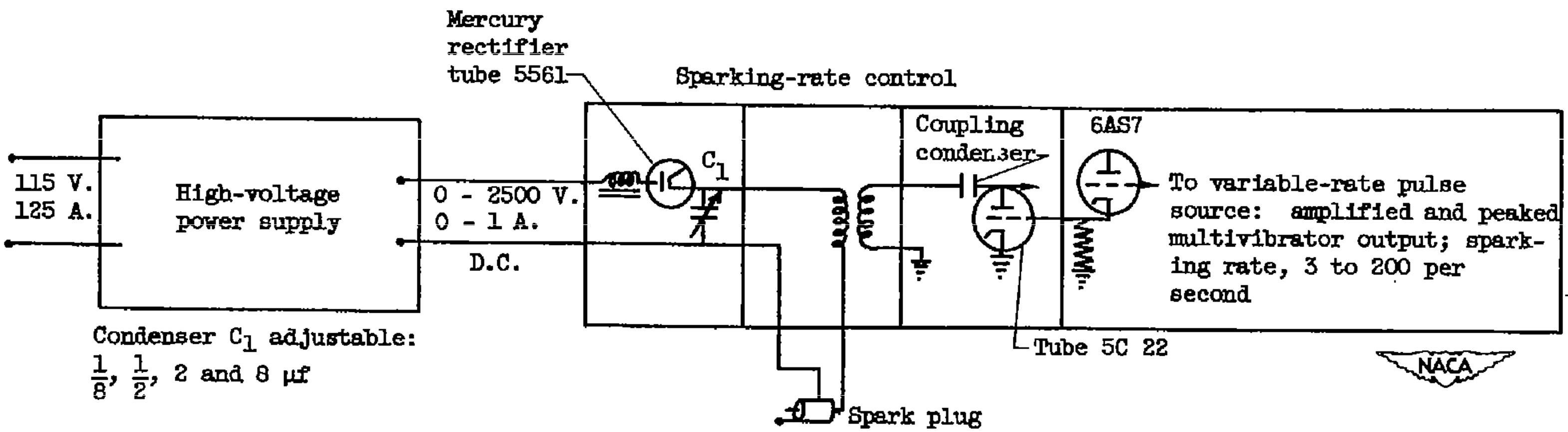

Figure 4. - Block diagram of high-energy ignition source and controls.

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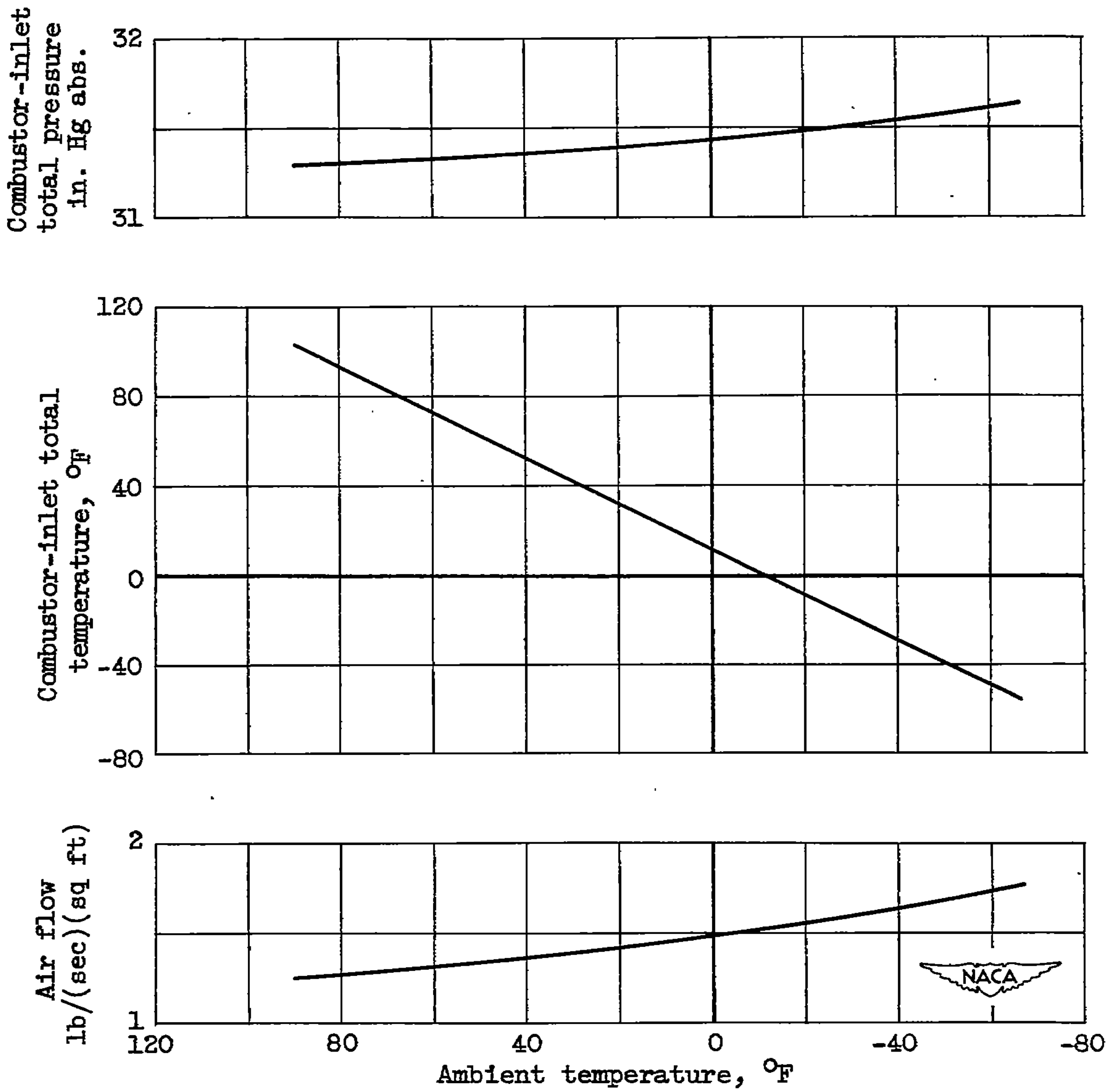

Figure 5. - Variation of air-flow parameters for single combustor. Simulated engine speed, 9-percent normal rated rpm; static sea-level conditions.

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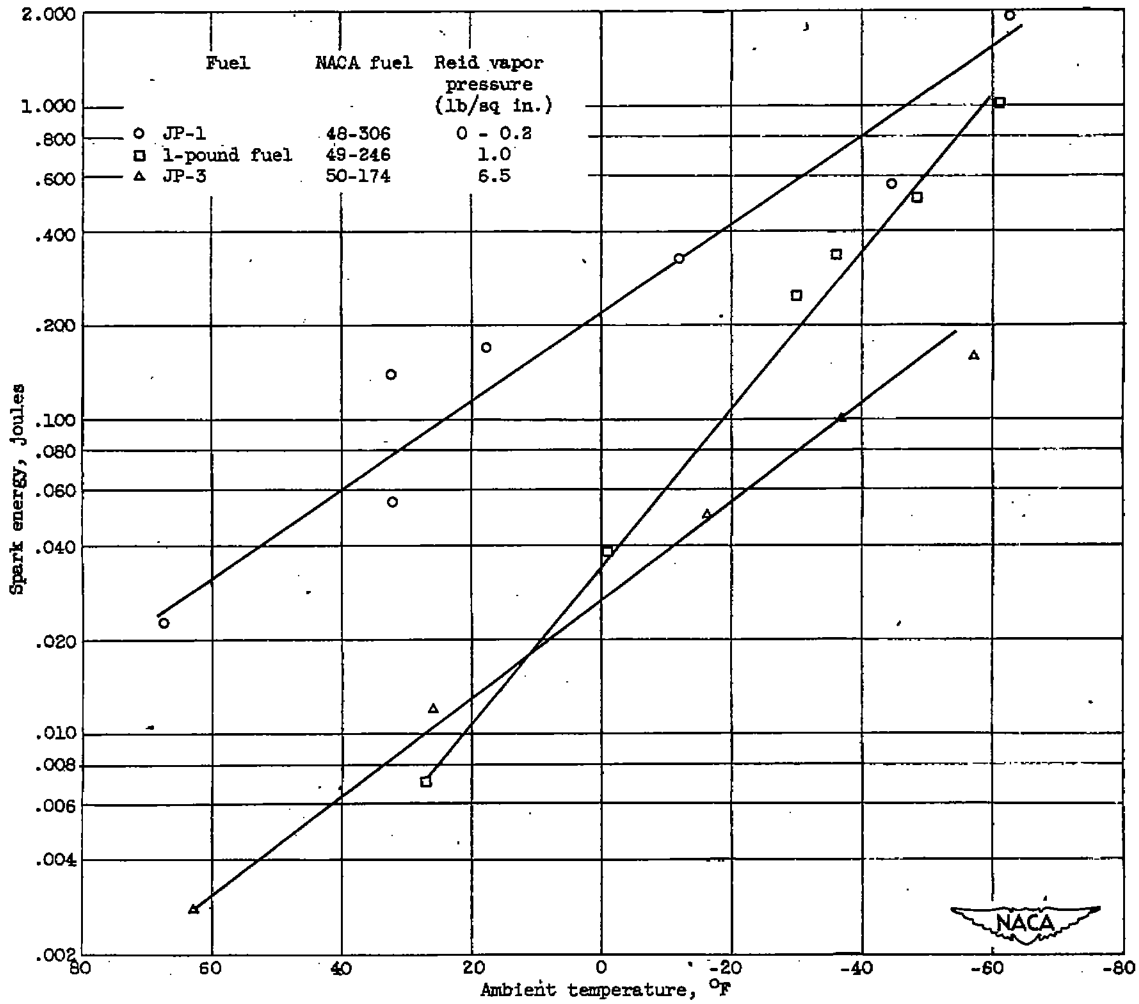

Figure 6. - Effect of ambient temperature on ignition of three fuels of different volatility at simulated engine cranking speed of 9-percent normal rated rpm and static sea-level conditions.

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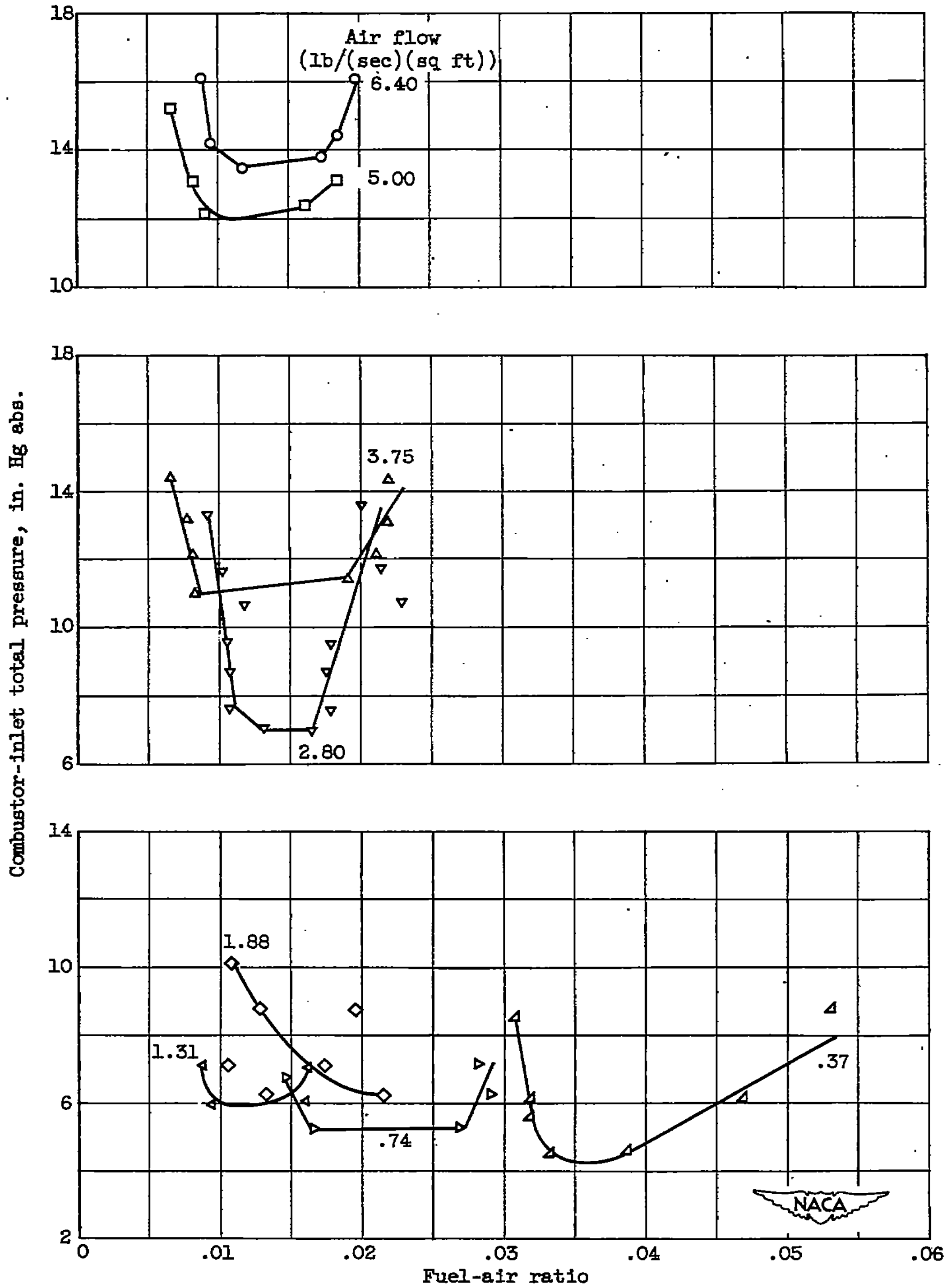
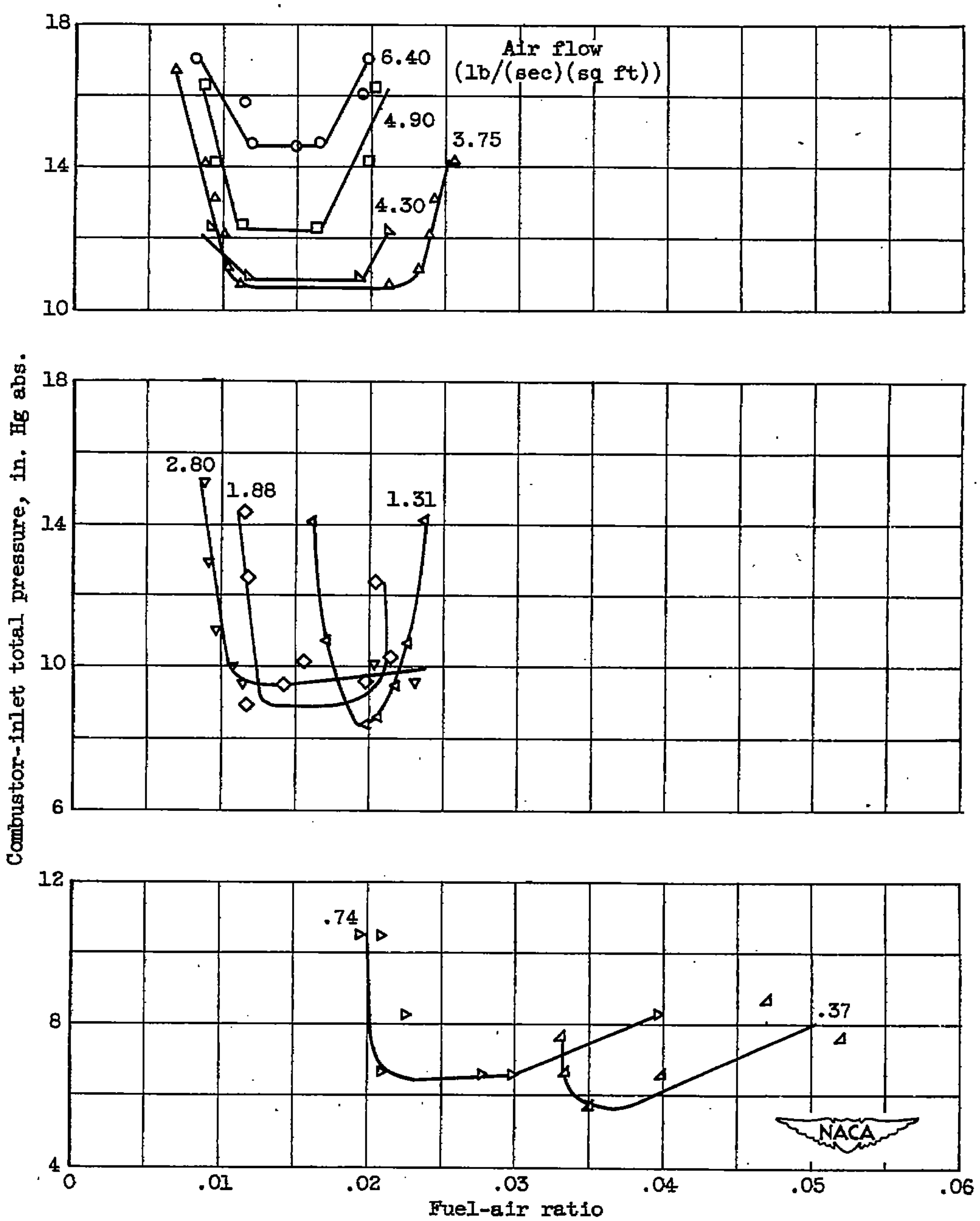


(a) JP-3 fuel (NACA fuel 50-174).

Figure 7. - Effect of air-flow rate and pressure on burning limits of single tubular combustor. Inlet-air temperature, -10° F; inlet-fuel temperature, -40° F.



(b) 1-pound fuel (NACA fuel 49-246).

Figure 7. - Continued. Effect of air-flow rate and pressure on burning limits of single tubular combustor. Inlet-air temperature, -10° F; inlet-fuel temperature, -40° F.

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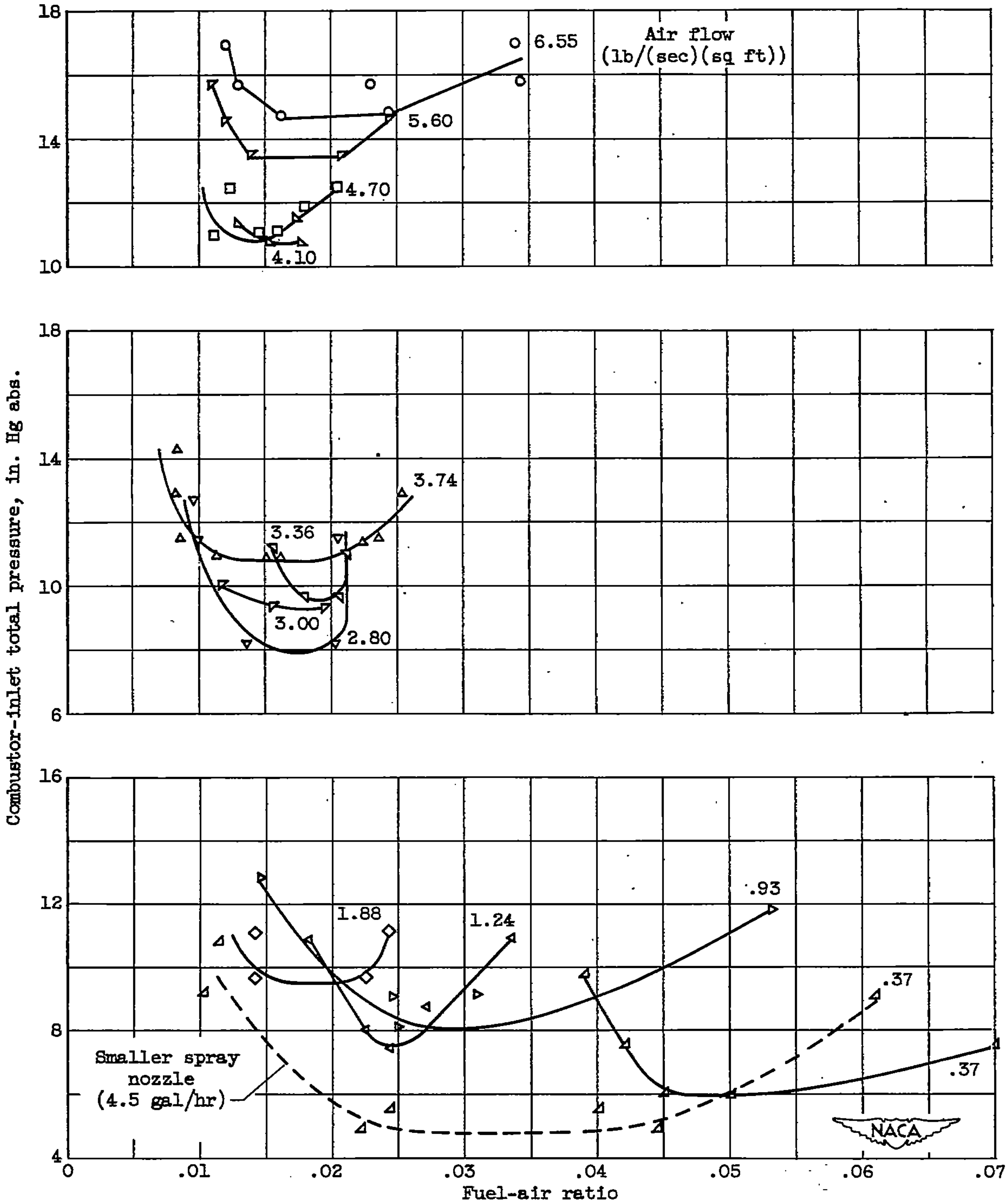

(c) JP-1 fuel (NACA fuel 48-306).

Figure 7. - Concluded. Effect of air-flow rate and pressure on burning limits of single tubular combustor. Inlet-air temperature, -10° F; inlet-fuel temperature, -40° F.

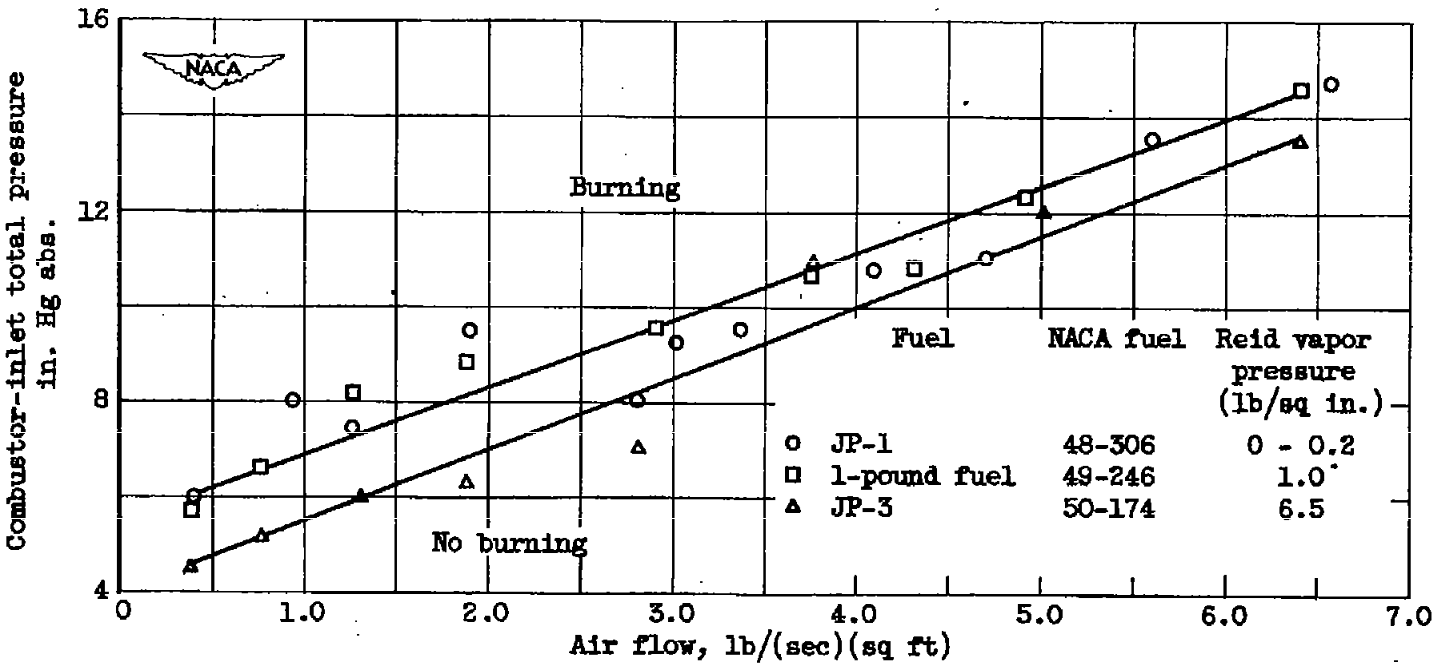

Figure 8. - Effect of fuel volatility, air-flow rate, and pressure on burning limits of single tubular combustor. Inlet-air temperature, -10° F; inlet-fuel temperature, -40° F.

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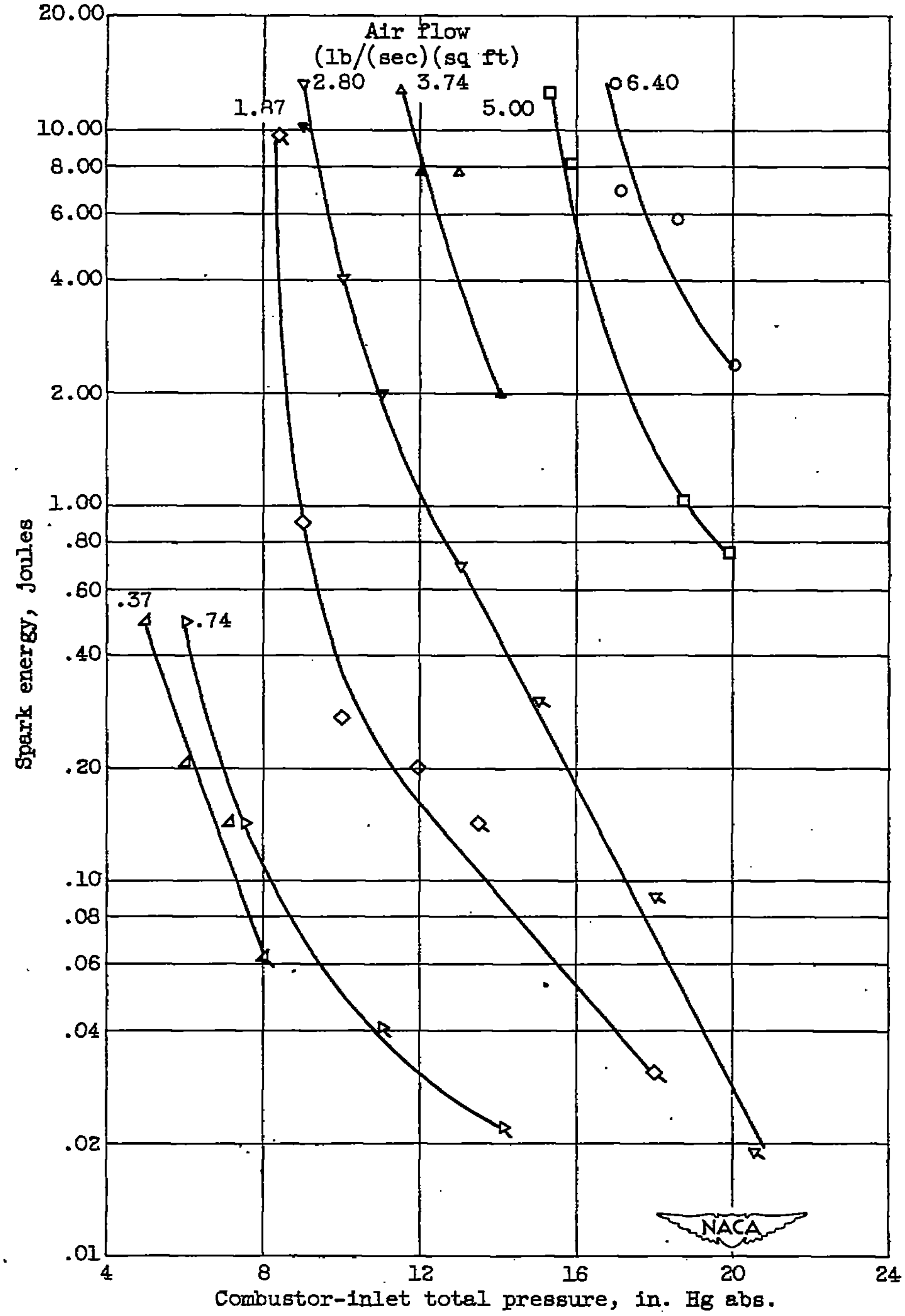

(a) JP-3 fuel (NACA fuel 50-174).

Figure 9. - Effect of air-flow rate and pressure on spark energy required for ignition in single tubular combustor. Inlet-air temperature, -10° F; inlet-fuel temperature, -40° F.

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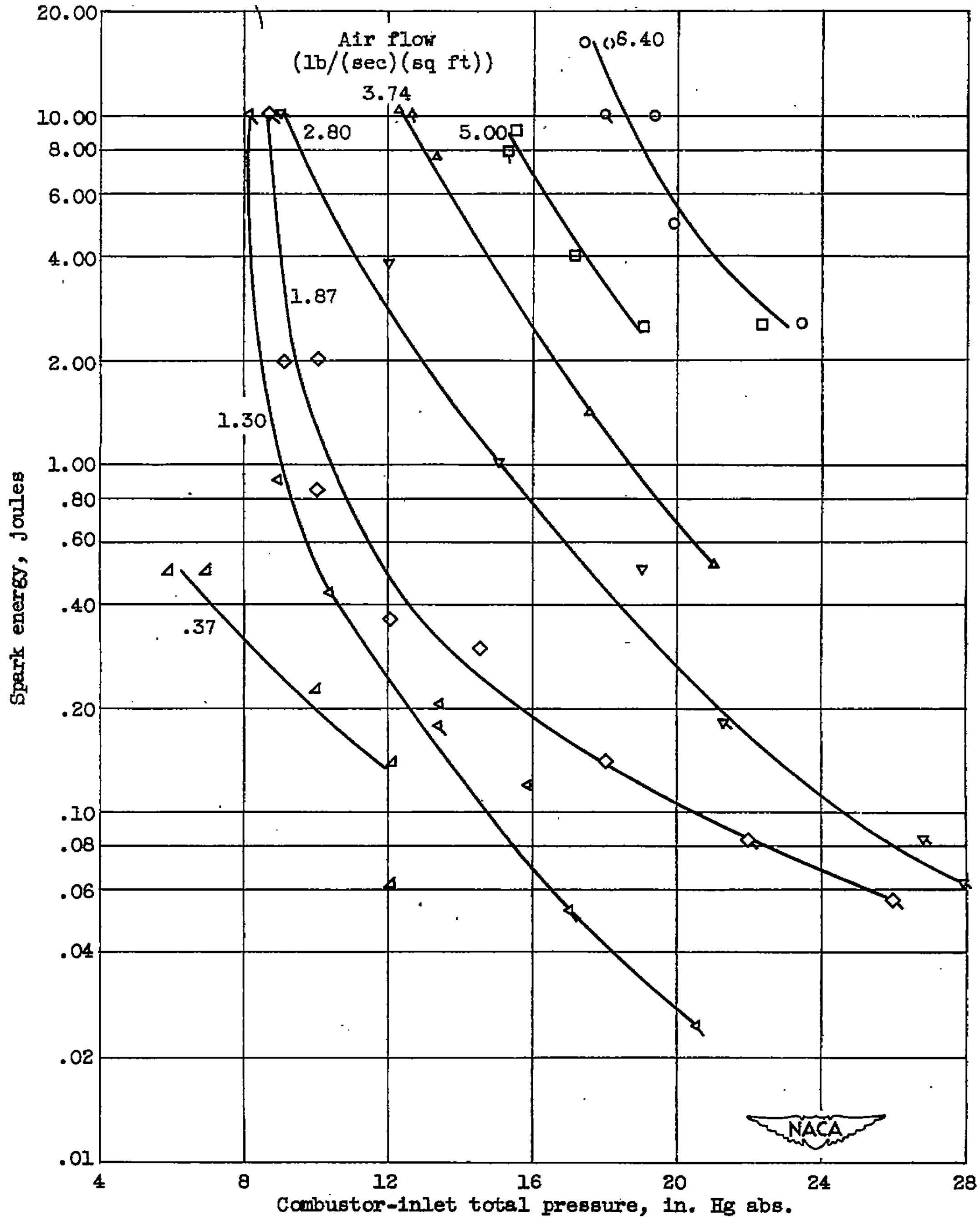

(b) 1-pound fuel (NACA fuel 49-246).

Figure 9. - Continued. Effect of air-flow rate and pressure on spark energy required for ignition in single tubular combustor. Inlet-air temperature, -10° F; inlet-fuel temperature, -40° F.

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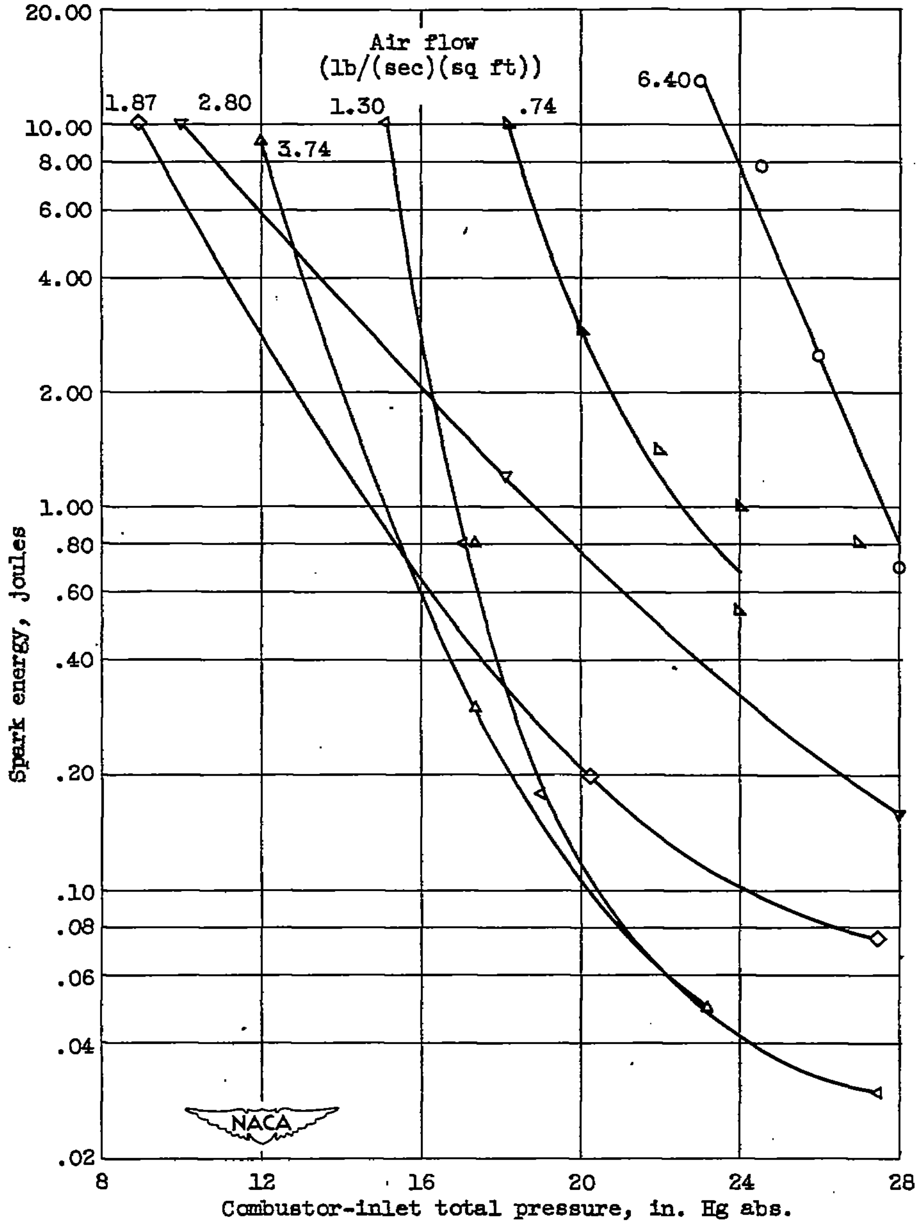
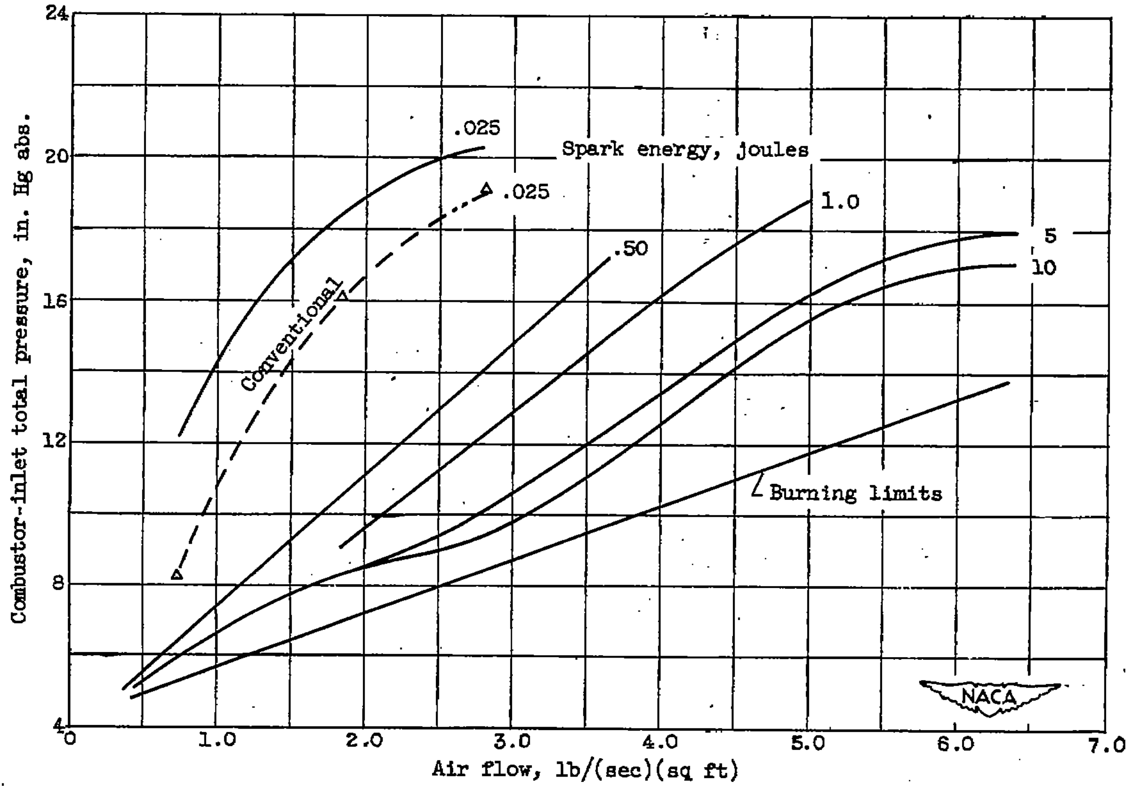


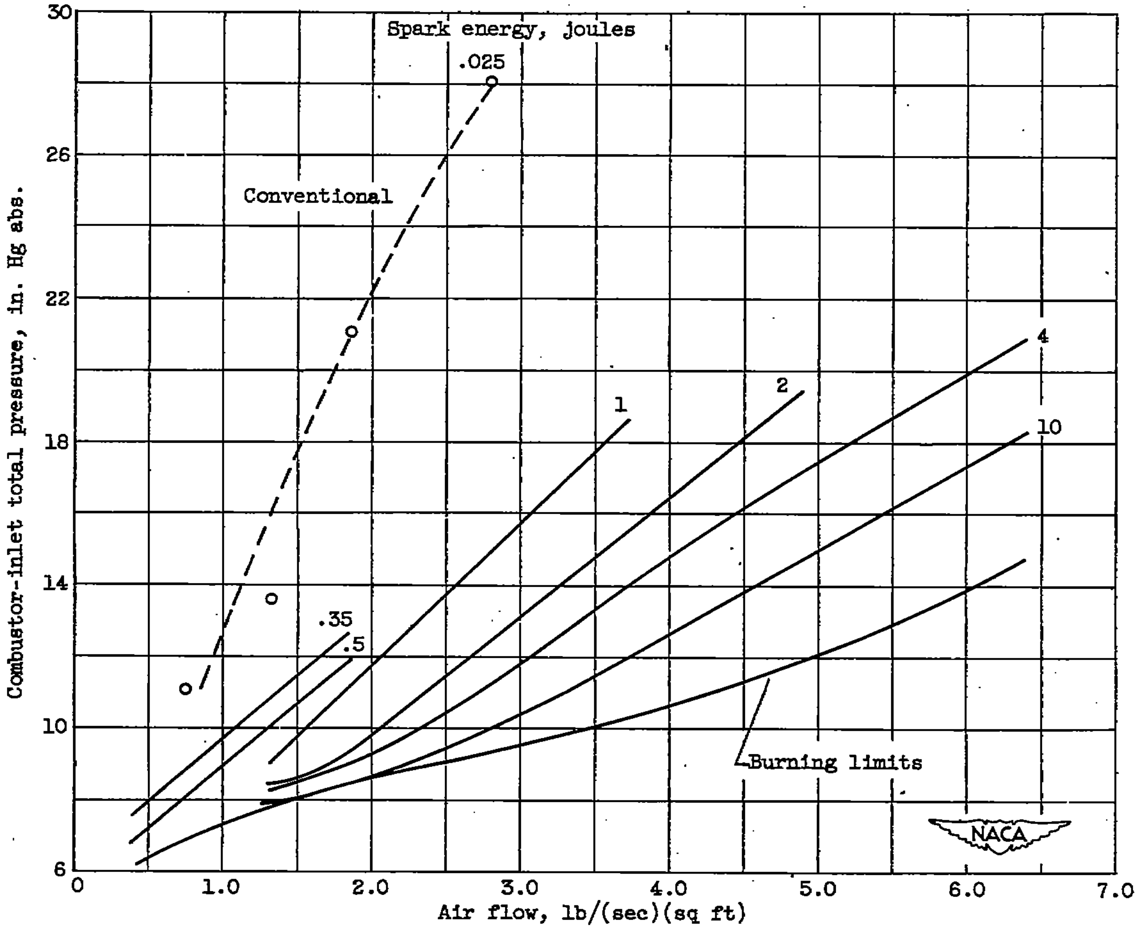
(c) JP-1 fuel (NACA fuel 48-306).

Figure 9. - Concluded. Effect of air-flow rate and pressure on spark energy required for ignition in single tubular combustor. Inlet-air temperature, -10° F; inlet-fuel temperature, -40° F.



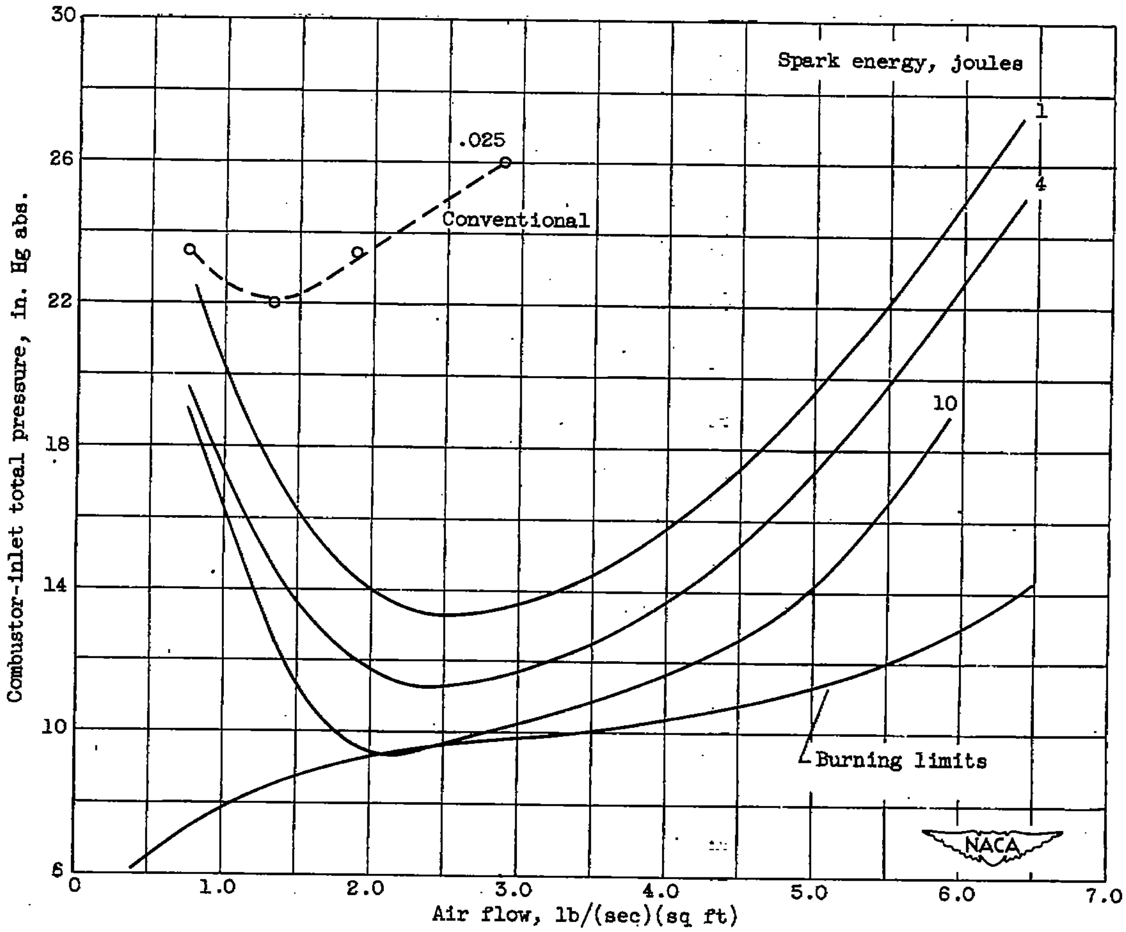
(a) JP-3 fuel (NACA fuel 50-174).

Figure 10. - Comparison of boundaries of ignition and burning limits of single tubular combustor. Inlet-air temperature, -10° F; inlet-fuel temperature, -40° F.



(b) 1-pound fuel (NACA fuel 49-246).

Figure 10. - Continued. Comparison of boundaries of ignition and burning limits of single tubular combustor. Inlet-air temperature, -10° F; inlet-fuel temperature, -40° F.



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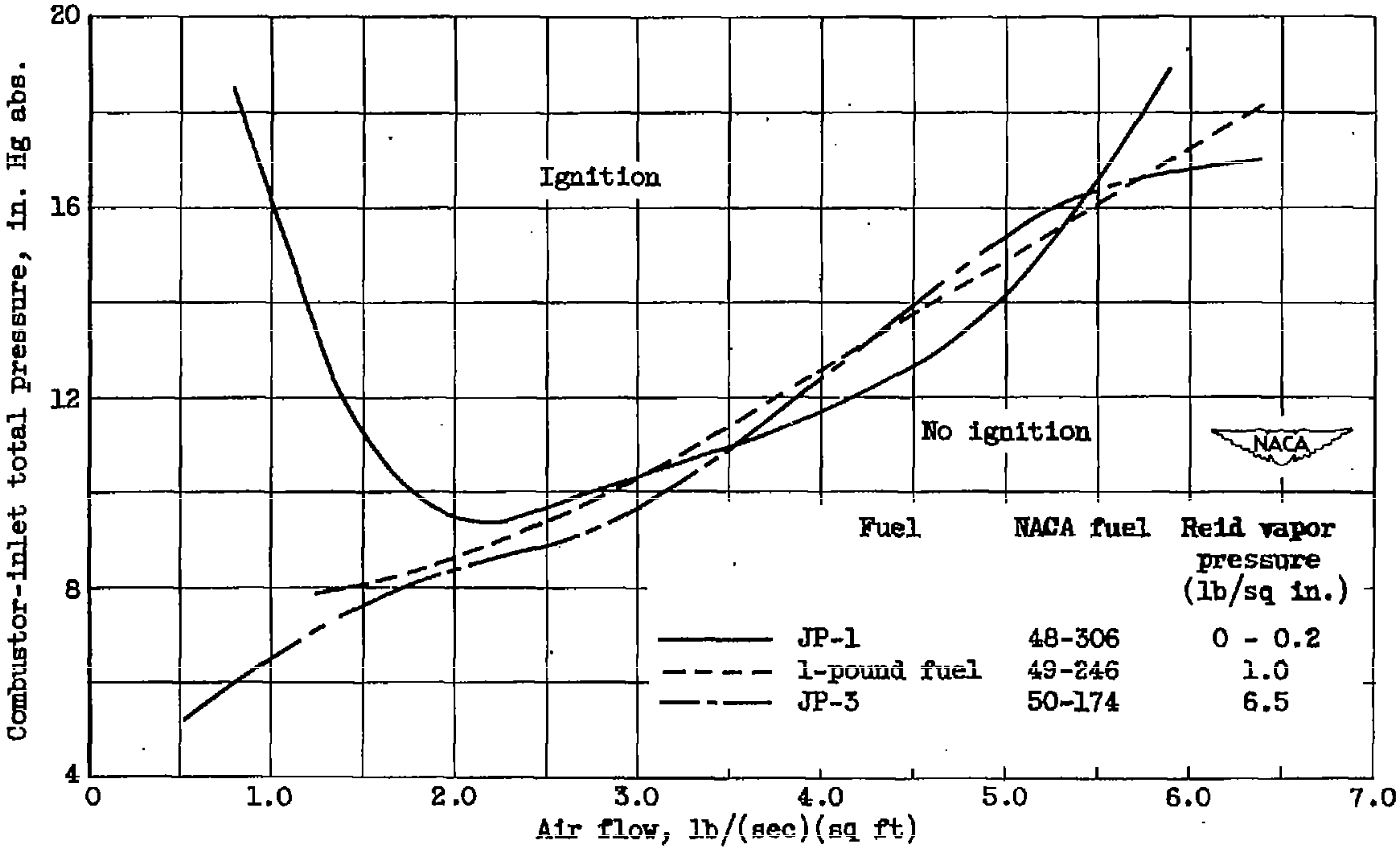

Figure 11. - Comparison of ignition limits in single tubular combustor for three fuels of different volatility. Spark energy, 10 joules; sparking rate, 7 to 8 per second; inlet-air temperature, -10° F; inlet-fuel temperature, -40° F.